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*by Robert W. Cubbison, Kenneth I. Davidson, Raymond A. Turk, and Everett C. Alexis*

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# EFFECT OF CANARDS IN REDUCING LAUNCH VEHICLE FLIGHT LOADS

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## SUMMARY

High structural loadings generally encountered by vehicles traversing the high wind shear regime may be reduced by the use of canards mounted on the launch vehicle. To demonstrate this possibility, a pair of trapezoidal canards mounted on a 1/23-scale model of the Atlas-Centaur-Surveyor configuration was tested in the Lewis 8- by 6-foot transonic wind tunnel. Data were obtained over the Mach number range of 0.55 to 1.96 for a model angle-of-attack range of $0^{\circ}$ to $10^{\circ}$ and canard deflection angle range of $10^{\circ}$ to $-40^{\circ}$. A rigid-body bending-moment analysis was performed to determine the reduction obtainable with canards both in the vehicle bending moments and in engine gimbal requirements. With the relatively small canard surfaces (ratio of canard planform area to reference area, $A_c/A_{ref}$, 0.226) of this study, significant reductions in applied bending moments were obtained over the Mach range investigated. For example, at Mach 1.96 with the canards deflected $-40^{\circ}$, the maximum applied bending moment was reduced from 114 percent to 10 percent of the design allowable values for $4^{\circ}$ angle-of-attack and from 196 percent to about 100 percent for a $7^{\circ}$ angle-of-attack. Along with the reduction in bending moments, there is a reduction in the engine gimbal requirement. The possibility of reducing engine gimbaling to zero with these canard surfaces was shown for a vehicle angle-of-attack of $5^{\circ}$.

## INTRODUCTION

In traversing the region of high wind shear, high vehicle angles of attack, and, consequently, large aerodynamic bending moments may be experienced. The possibility exists of utilizing a canard installation to alleviate these severe structural loadings and gimbal requirements imposed on launch vehicles. Canards are aerodynamic surfaces which, if mounted on a launch vehicle in both the pitch and yaw planes, can be used to generate moments about the vehicle center of gravity in opposition to the vehicle aerodynamic moments. By incorporating a differential rotation capability in the canard system, it is possible to achieve roll control along with pitch and yaw control as suggested in reference 1. Since the canard surfaces would be ineffective at launch and in space, engine gimbaling or a reaction control device would still be required.

The present investigation was undertaken to study a pair of canards and their effect in reducing vehicle bending moments. Although two sets of surfaces are necessary on the basis of vehicle control, only one set was required to achieve the purpose of this study. The launch vehicle selected for this study was the Atlas-Centaur with the Surveyor payload shroud. A 1/23-scale model of this vehicle was tested in the Lewis 8- by 6-foot transonic wind tunnel without canards and also with two trapezoidal canards installed $180^{\circ}$ apart. Experimental data were obtained over the following ranges of variables: canard deflection angles of $10^{\circ}$ to $-40^{\circ}$, Mach numbers of 0.55 to 1.96, and vehicle angles-of-attack of $0^{\circ}$ to $10^{\circ}$. The tunnel Reynolds number per foot varied from $3.58\times10^{6}$ at Mach 0.55 to $4.98\times10^{6}$ at Mach 1.96.

A rigid-body bending-moment analysis was performed to determine the reduction in vehicle bending moments which is possible with installation of canards on this particular launch vehicle. In addition, the effect of canards on the engine gimbal angle required to trim the vehicle was determined.

## SYMBOLS

$A_c$ canard planform area (scale model), 4.838 sq in.

$A_{ref}$ full-scale reference area (based on cylindrical cross section of Atlas), 11 310 sq in.; model reference area (based on cylindrical cross section of Atlas), 21.380 sq in.

$C_{F_A}$ total axial-force coefficient, $F_A/q_oA_{ref}$

$C_{F_N,c}$ canard incremental normal force coefficient, $F_N/q_oA_{ref}$

$C_{L,c}$ canard incremental lift coefficient, $L/q_oA_c$

$F_A$ total axial-force, lb

$F_N$ incremental canard normal force, lb

$L$ incremental canard lift, lb

$M_d$ design allowable bending moment, in.-lb

$M_o$ free-stream Mach number

$M_u$ ultimate allowable bending moment, in.-lb

$q_o$ dynamic pressure, lb/sq in.

$\alpha_c$ canard angle-of-attack measured relative to free stream (see fig. 2(c)), deg

$\alpha_v$ vehicle angle-of-attack measured relative to free stream (see fig. 2(c)), deg

$\delta_c$ canard deflection angle measured with respect to the vehicle centerline (see fig. 2(c)), deg

$\sigma$ vehicle engine gimbal angle, deg

## APPARATUS AND PROCEDURE

The 1/23-scale model of an Atlas-Centaur-Surveyor configuration with canards is shown in the transonic test section of the Lewis 8- by 6-foot wind tunnel in figure 1. The model was sting-mounted on a three-component force balance. Details of the canards, their locations on the model, and the coordinate system used in the present tests are shown in figure 2. The design of the canards was based on the data presented in reference 2. The resulting trapezoidal-shape canards had an aspect ratio of 2.0 and a thickness of 4.07 percent of the root chord. They were located $180^\circ$ apart on the horizontal centerline of the vehicle as mounted in the wind tunnel. The hinge line was located on the barrel section of the Surveyor payload shroud at model station 10.146. Because of the protuberances in this region, the canards (for ease of installation on the existing model) were mounted in the actual vehicle yaw plane. In the present study, this orientation will be called the test pitch plane (fig. 2(b)). The total planform area (17.76 sq ft, full scale) was sized to produce a normal force of approximately half that generated by the vehicle at Mach 1.4 and a $5^\circ$ angle-of-attack. These conditions are most likely to occur in the regions of high wind shear.

Canard deflection angle as well as the vehicle angle-of-attack was remotely variable. Prior to the force test with and without canards, the model was extensively instrumented with pressure taps and tested in the Lewis 8- by 6-foot transonic wind tunnel to determine the normal airload distribution in both the vehicle pitch and yaw planes. The results of that investigation are reported in reference 3.

## RESULTS AND DISCUSSION

A series of force tests was conducted to determine the canard contribution to the normal and axial airloads on a launch vehicle. These force increments were then combined with the distributed normal and axial airloads of the vehicle to determine canard effectiveness in reducing the applied bending-moment and engine gimbal requirements.

The airloads used in this study were obtained from reference 3 with the distributed normal values being those obtained with the vehicle in the same orientation as shown in figure 1.

## Canard Aerodynamic Characteristics

The variation of canard incremental lift coefficient $C_{L,c}$ with canard angle-of-attack $\alpha_c$ at various model angles-of-attack are presented in figure 3 for Mach numbers of 0.55 to 1.96. The values were obtained by subtracting the total lift coefficient without canards from that with the canards installed. These increments were then referenced to the canard planform area. Since this procedure includes the effect of canards on the overall vehicle pressure distribution, the data of figure 3 are the lift increments on the vehicle generated by the canards rather than the pure lift coefficients of the canards. Generally, these data indicate that increasing the vehicle angle-of-attack $\alpha_v$ results in an increase in the canard lift curve slope and a decrease in the canard zero lift angle. At Mach 1.0, for example, the canard lift curve slope at an $\alpha_v$ of $10^{\circ}$ is approximately 64 percent greater than the slope of the curve for $\alpha_v$ equal to zero. Also, the change in the lift curve slopes decreases as the speed is either increased or decreased from Mach 1.0. The greatest change in the zero lift angle (about $1^{\circ}$ per degree change in $\alpha_v$) occurs at Mach 0.8. In general, the change at the other Mach numbers investigated is approximately $0.5^{\circ}$ per degree $\alpha_v$. These trends are a direct result of the flow upwash generated when the vehicle is at some angle-of-attack other than zero. Both the changes in canard zero lift angle and lift curve slope are within the range predicted for supersonic flow in reference 4. In regard to the use of canards as proposed herein, the net result of the zero lift angle change is to require larger canard deflections to produce a given lift increment as the vehicle angle-of-attack is increased. This effect is apparent from figure 3 for the canard angle-of-attack range of $0^{\circ}$ to about $-10^{\circ}$. The increase in lift curve slope produces the opposite effect in that less canard deflection is required to produce a given lift increment as the vehicle angle-of-attack is increased. This effect is also apparent from figure 3 for the negative canard angle-of-attack range greater than about $-15^{\circ}$. In general, these contrasting effects (zero lift angle change and increasing lift curve slope) essentially nullify each other in the canard angle-of-attack range from approximately $-10^{\circ}$ to $-15^{\circ}$.

The canard normal force contribution to the total vehicle airload including the canard effect on the vehicle pressure distribution was obtained by subtracting the total normal force coefficient of the basic model without canards from the value at comparable conditions for the canard-equipped model. For illustrative purposes, only the results at Mach 1.36 are presented in figure 4, since similar trends were noted at the other test conditions. These data are then used as the canard contribution to the rigid-body bending-moment analysis discussed in the next section.

Figure 5 presents the total axial-force coefficients also used in the bending-moment analysis. Values for the no-canard configuration, which include an engine operating base force, were obtained from reference 3. The increments due to the canards (which were determined from the present study) were added to the no-canard configuration (ref. 3) to determine the overall axial force of the vehicle for various canard deflections. The presence of canards increases the axial force of the vehicle and an additional increment is generated by canard deflection. For a canard deflection of $-40^{\circ}$, the axial-force coefficient is increased about 0.15 for a $7^{\circ}$ angle-of-attack in both the subsonic and supersonic range and about 0.24 in the transonic speed range.

Since the model used in this investigation was an Atlas-Centaur-Surveyor configuration, the dynamic pressure, Mach number schedule (fig. 6) of a typical flight trajectory was used in the rigid-body bending-moment analysis.

## Canard Effect on Bending-Moments and Engine Gimbal Requirements

The applied bending moments were obtained by utilizing a computer program to determine a rigid-body bending-moment distribution. The program requires the following inertial and aerodynamic inputs: vehicle weight, engine thrusts, dynamic pressure, and aerodynamic forces for an assumed angle-of-attack at each Mach number considered. The total vehicle weight was divided into a sufficient number of discrete weights to approximate the actual weight distribution of the vehicle. The canard aerodynamic contribution was obtained from results of the present investigation, while the vehicle aerodynamic forces and their distribution were obtained from reference 3. In this analysis, the incremental canard forces, which include the effects on the vehicle pressure distributions, were assumed to act as a concentrated load at the canard hinge line.

For the assumed conditions, the program computes the shear load, the applied bending moment, and the axial compression as functions of vehicle station and also the gimbal angle required to maintain vehicle trim. The shear load at a station is the sum of the lateral inertial loads and the aerodynamic normal forces acting on that portion of the vehicle ahead of the station. The applied bending moment at a station is calculated by considering only shear loads acting forward of that station. This is done by summing all the products of each inertial and aerodynamic load times its distance from the station at which the moment is desired. The axial compressive loads at a station are the sum, in the axial direction, of the distributed inertial loads and the aerodynamic axial forces ahead of the station. All computations were made for the vehicle in the trimmed condition at the angle-of-attack under consideration. In the computer program, trimming of the vehicle was accomplished by engine gimbaling.

Since the Atlas-Centaur vehicle uses pressure stabilized tankage, its ability to carry external loads is primarily a function of propellant tank pressures. Internal pressure prevents collapse of the tank walls by introducing longitudinal tensile stresses. External axial force and bending moment introduce longitudinal stresses in opposition to these tensile stresses. Ultimate strength capability is then determined by limiting the net amount of longitudinal compression in the tank walls in order to prevent wall buckling or collapse. For the purpose of this study, Centaur ultimate strength was calculated assuming that no net compressive stress can be induced into the fuel tank wall. Since the Atlas tank walls are somewhat thicker than those of Centaur, a small amount of compressive stress (less than that which produces buckling) was permitted in evaluating the ultimate strength capability of the oxidant and fuel tank skins. A recent test of the Atlas stage indicates that the oxidant tank is capable of carrying compressive loads even after buckling, but no advantage of post-buckling strength capability was considered in this study. Ultimate strength was divided by a factor of safety of 1.25 to obtain the design allowable strength. For this study, the load-carrying capability of the Centaur liquid-hydrogen tank was based on a typical minimum ullage pressure schedule. During the early phase of flight, the hydrogen tank pressure regulator valve is locked closed, and the tank pressure increased (due to heat input) from about 20 psia at lift-off to a maximum of about 24 psia. Then at about Mach 1.4, in our study, the valve is unlocked and the minimum tank pressure drops to about 20 psia. For the Atlas, the assumed minimum ullage pressures were 28.5 psig in the liquid-oxygen tank and 57 psig in the RP-1 tank.

In order to demonstrate the load relief capability of the canard concept, applied vehicle bending moments and required engine control deflections for trim over the Mach range 0.55 to 1.96 were calculated for a vehicle angle-of-attack range of $2^{\circ}$ to $7^{\circ}$. The analysis of the no-canard data at $\alpha_v$ of less than $4^{\circ}$ indicated bending moments below the design allowable limits; hence, the results are not shown. The results at $\alpha_v = 4^{\circ}$ and $7^{\circ}$ are shown in figures 7 and 8, respectively. In these figures, the allowable bending moments are plotted as a function of vehicle station for configurations with and without canards. The design allowable bending moment represents the remaining design strength capability after due consideration has been given to the axial compression loads arising from longitudinal inertial loads and aerodynamic axial forces. For the configuration with canards, these axial compression loads include the additional effects due to canard inertia plus the canard aerodynamic axial force, which increases with canard deflection. The vehicle is considered structurally adequate if the applied bending moment is less than the design allowable value. For $\alpha_v = 4^{\circ}$ (fig. 7), the applied bending moment without canards equals or exceeds the design allowable values in the 1.56 to 1.96 Mach range. Therefore, under the assumption of the tank ullage pressures previously cited, the Atlas-Centaur-Surveyor vehicle of this study without canards would be limited to a total angle-of-attack of less than $4^{\circ}$.

In general for $\alpha_v = 7^{\circ}$ (fig. 8), canard deflections of $-20^{\circ}$ reduced the applied bending moments below design allowable values for Mach numbers less than 1.36. At Mach numbers of 1.36 and greater, canard deflections up to approximately $-40^{\circ}$ would be required. For a vehicle angle-of-attack of $4^{\circ}$ (fig. 7) the canards used in this study ($A_c/A_{ref} = 0.226$) reduced the applied bending moment at vehicle station 750 from 114 percent to 10 percent of the design allowable value at Mach 1.96. At a $7^{\circ}$ vehicle angle-of-attack (fig. 8), the applied bending moment is reduced from 196 percent to about 100 percent of the design allowable value with a $-40^{\circ}$ canard deflection. Based on these results, the angle-of-attack capability could be increased from $4^{\circ}$ to $7^{\circ}$ with these particular canards. Further angle-of-attack capability could be obtained by increasing the canard planform area. However, the determination of the best canard size involves consideration of many factors such as the effect on payload capability, necessary actuator forces, drag loads, etc., which are beyond the scope of this report.

The amount of engine gimbaling required to trim the vehicle at an angle-of-attack of $5^{\circ}$ and $7^{\circ}$ as affected by canard deflection is shown in figure 9. With canards added to the vehicle, a reduction in engine gimbal required for trim can be obtained. If the proper amount of canard deflection is used, the engine gimbal requirement can be reduced to zero over the Mach range studied for an $\alpha_v$ of $5^{\circ}$ (fig. 9(a)). At a $7^{\circ}$ vehicle angle-of-attack (fig. 9(b)), significant reduction in gimbal angle requirements were also obtained; however, larger canards would be required to achieve zero engine gimbal over the entire Mach range studied.

## CONCLUDING REMARKS

The potential capability of a canard system to significantly reduce the applied bending moments and engine gimbal requirements of a launch vehicle over the 0.55 to 1.96 Mach range is shown herein. The Atlas-Centaur-Surveyor configuration is used in this analysis. For a vehicle angle-of-attack of $4^{\circ}$, without canards, the applied bending moment is above the design allowable values in the Mach 1.56 to 1.96 range. With the pair of canards used in this study (ratio of canard planform area to reference area, $A_c/A_{ref}$, 0.226) it is possible to reduce the applied bending moment at Mach 1.96 from 114 percent of the design allowable value to 10 percent with a $-40^{\circ}$ canard deflection. At a $7^{\circ}$ vehicle angle-of-attack, the applied bending moment without canards exceeded the design allowable values at Mach numbers equal to or greater than 1.0. With the canards deflected $-40^{\circ}$ at Mach 1.96, the applied bending moment was reduced from 196 percent to approximately 100 percent of the design allowable values. As a result of the reductions, the angle-of-attack capability was accordingly increased from $4^{\circ}$ to approximately $7^{\circ}$.

The relatively small canard area used in this study is notable. For purposes of this study, the full-scale planform area was 8.88 square feet per fin. Increasing the canard planform area could give still greater reductions in bending moment and, hence, could increase the allowable angle-of-attack.

In a comprehensive study of the applications of such canards to a vehicle, many factors (such as the effect on vehicle payload capability, complex control system design, acturator forces, engine gimbal limitations, etc.) must be considered which were beyond the scope of the present effort.

The use of canards reduced engine gimbal requirements for flight in the sensible atmosphere. At a vehicle angle-of-attack of $5^{\circ}$, the canards reduced the engine gimbal requirement to zero, therefore, the canards could provide vehicle trim. To provide this trim capability at a vehicle angle-of-attack of $7^{\circ}$, the canard planform area would have to be increased. Since the canards are aerodynamic devices, they would be ineffective at launch and in space. Consequently, either thrust vector control or a separate reaction control system would also be needed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 18, 1967,
891-05-00-01-22.

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4. Beskin, L.: Determination of Upwash Around a Body of Revolution at Supersonic Velocities. Rep. No. CM-251, Johns Hopkins Univ., Applied Physics Lab., Consolidated Vultee Aircraft Corp., DEVF Memo BB-6, May 27, 1946.

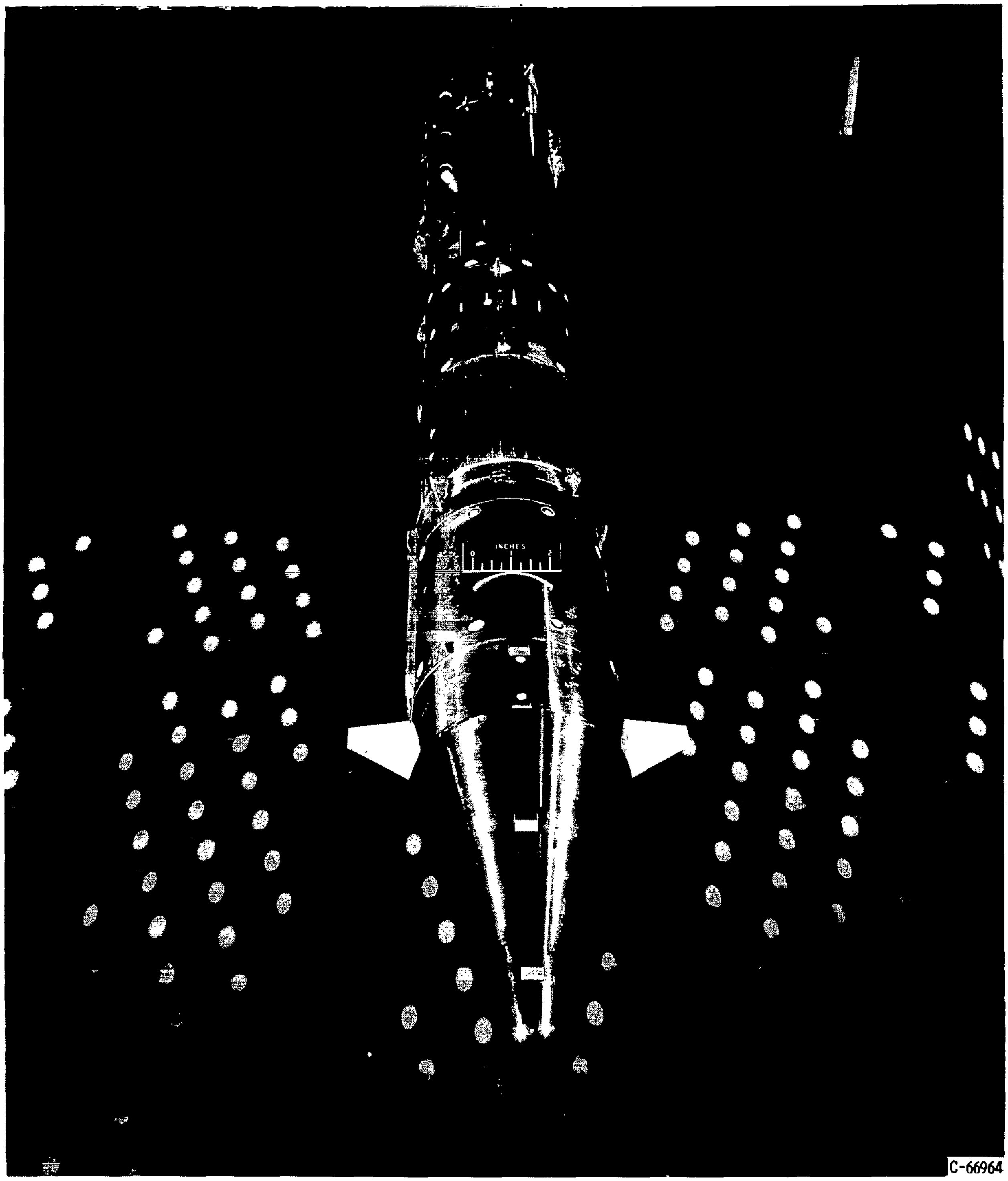
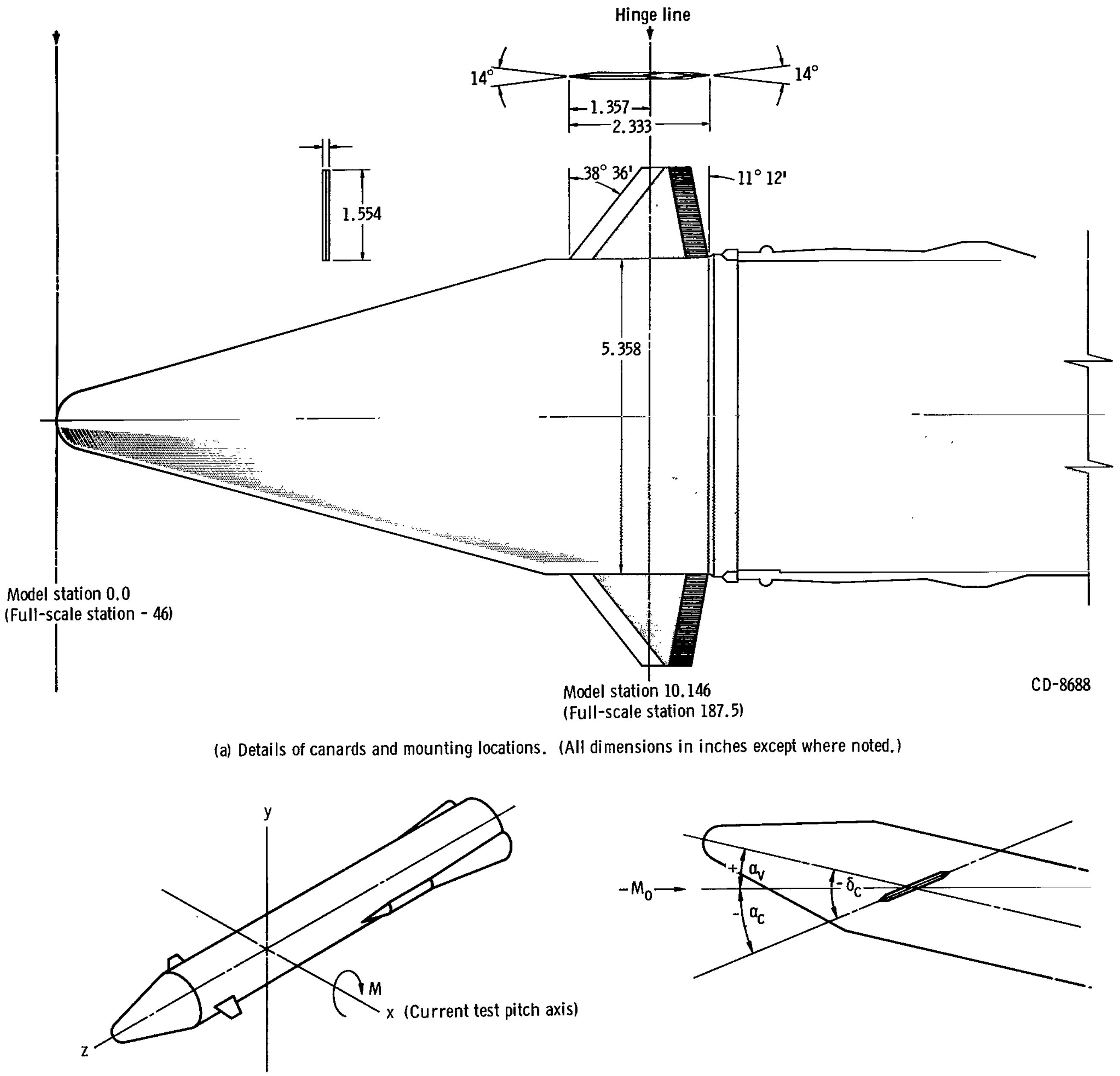



Figure 1. - Top view of installation of 1/23-scale Atlas-Centaur-Surveyor model with canards in 8- by 6-foot wind tunnel.



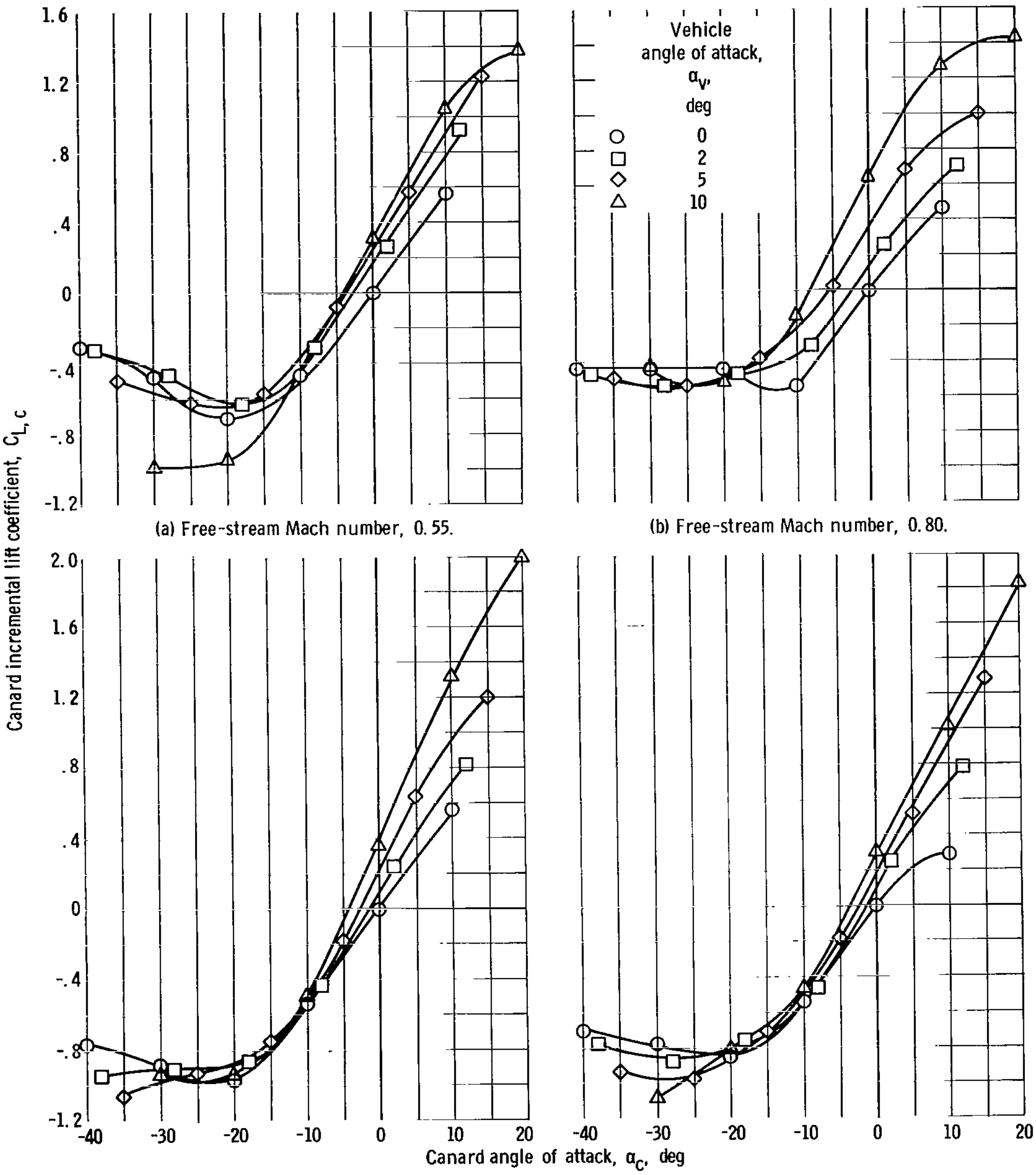

(a) Details of canards and mounting locations. (All dimensions in inches except where noted.)



(b) Axis system.

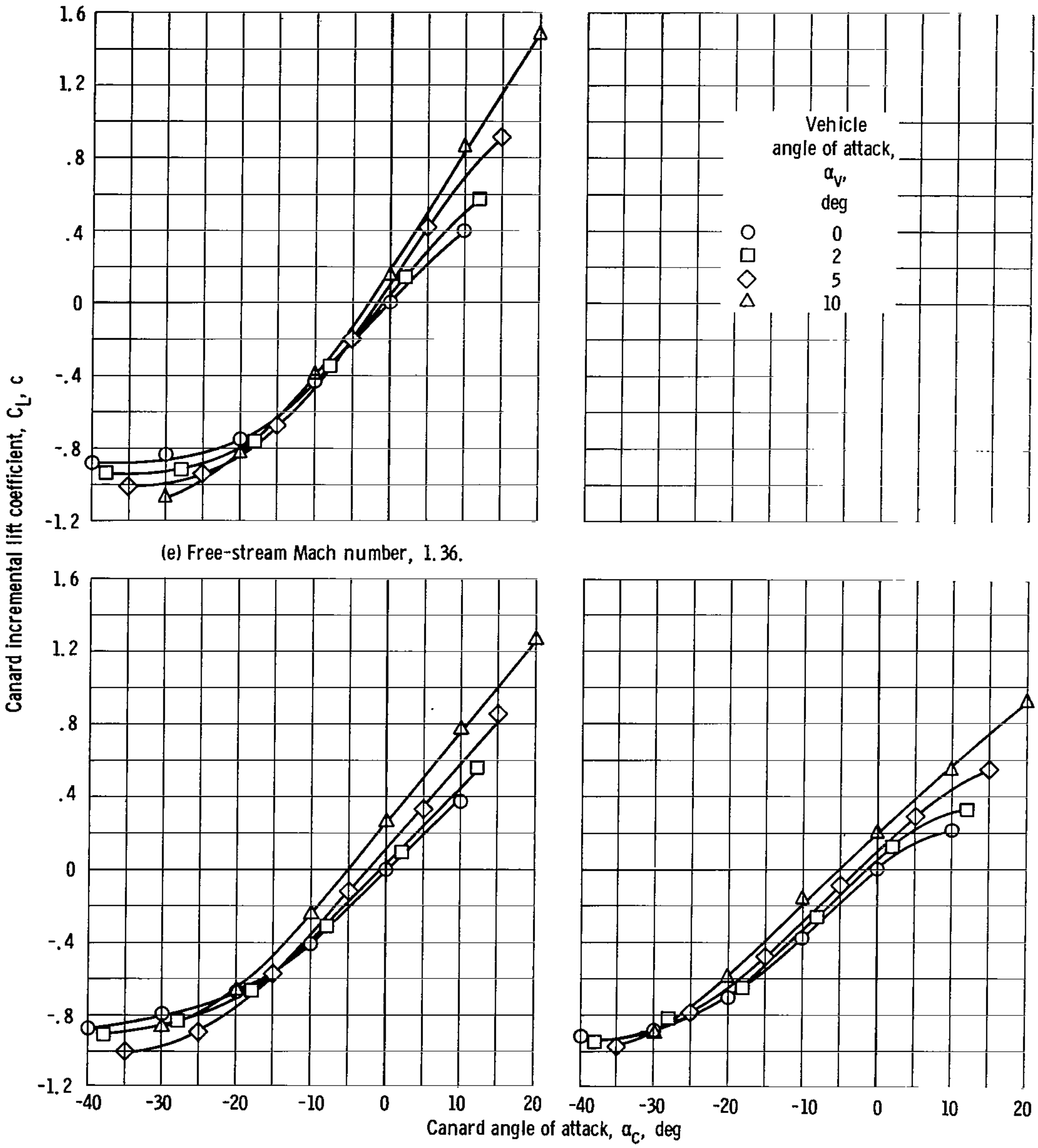
(c) Canard and vehicle angular relation.

Figure 2. - Canards, canard locations, and axis system on 1/23-scale model of Atlas-Centaur-Surveyor configuration.




(c) Free-stream Mach number, 1.0. (d) Free-stream Mach number, 1.2.

Figure 3. - Variation of canard incremental lift coefficient with canard angle of attack.




(e) Free-stream Mach number, 1.36.

(f) Free-stream Mach number, 1.56.

(g) Free-stream Mach number, 1.96.

Figure 3. - Concluded.

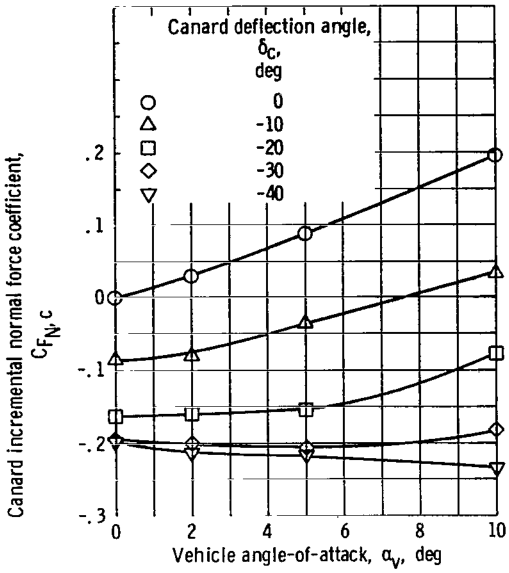



Figure 4. - Canard normal force contribution at free-stream Mach number of 1.36.

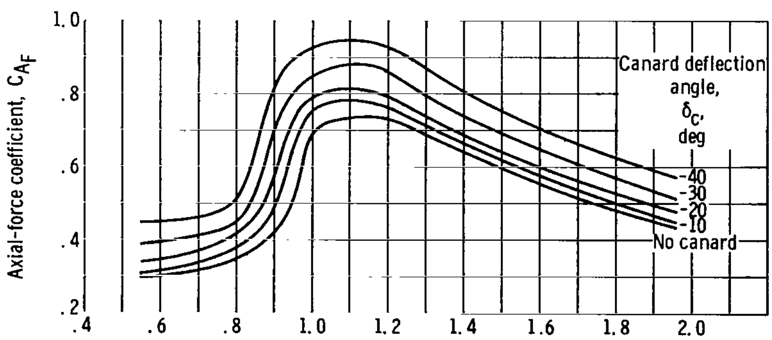



Figure 5. - Comparison of axial-force coefficient for vehicle with and without canards at 7° vehicle angle-of-attack.

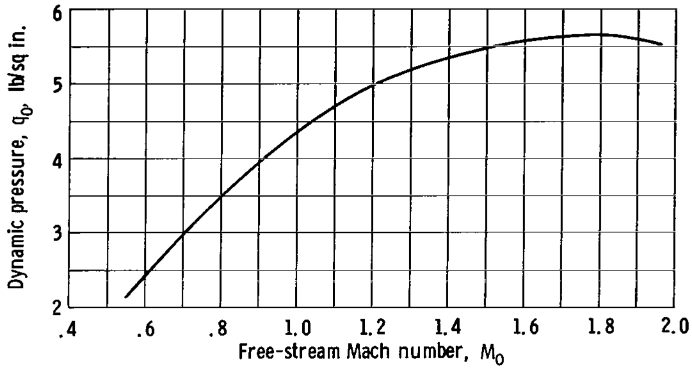
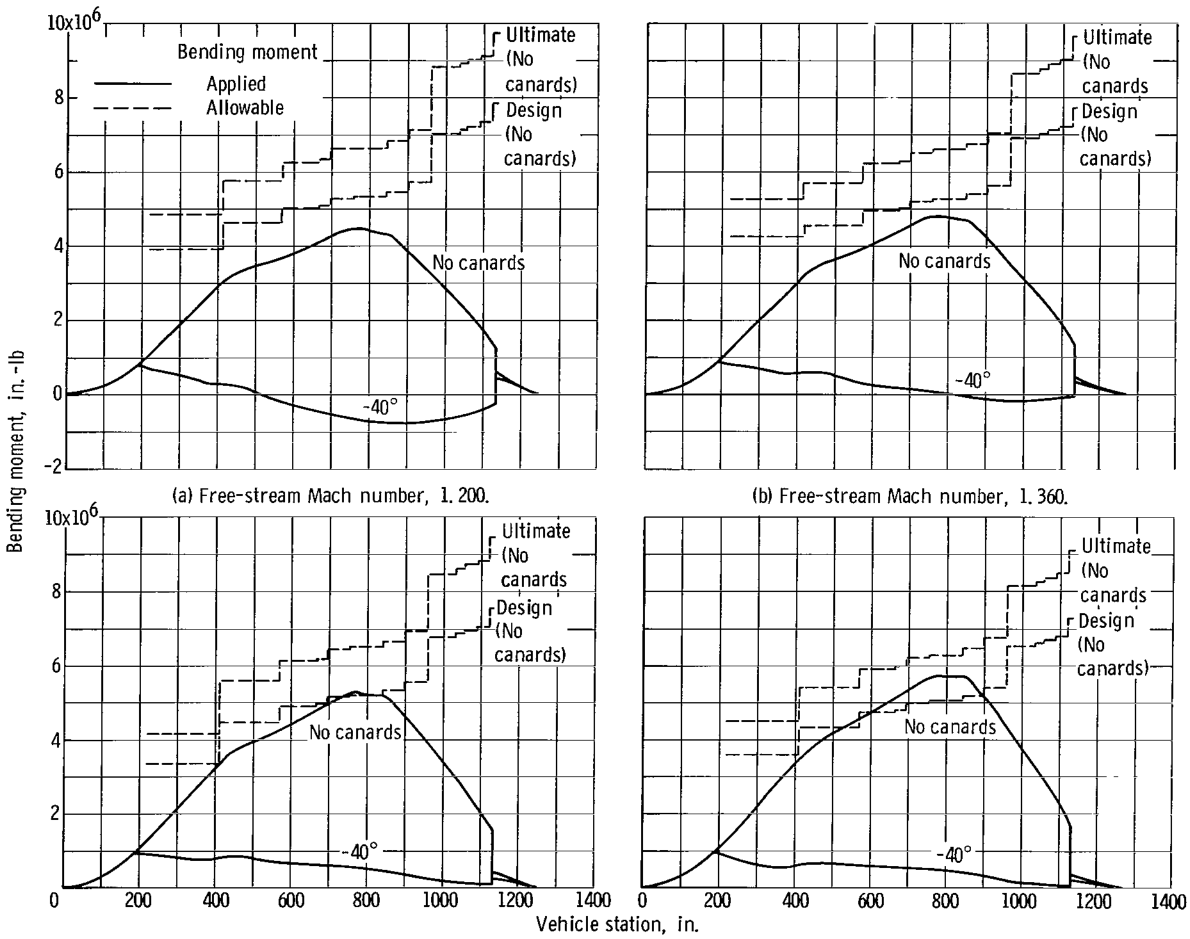



Figure 6. - Variation of dynamic pressure for typical Atlas-Centaur-Surveyor trajectory.



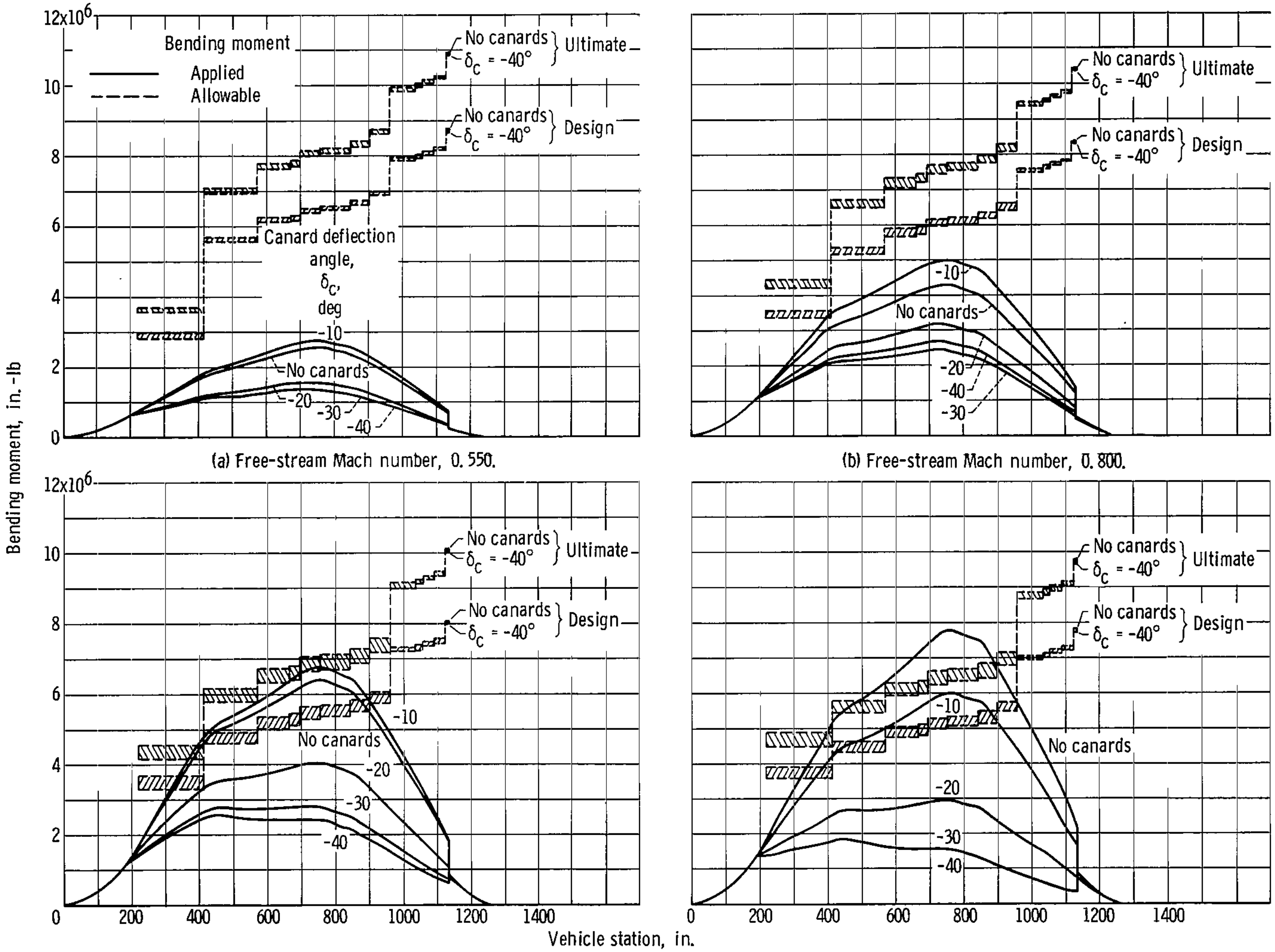

(a) Free-stream Mach number, 1.200.

(b) Free-stream Mach number, 1.360.

(c) Free-stream Mach number, 1.560.

(d) Free-stream Mach number, 1.960.

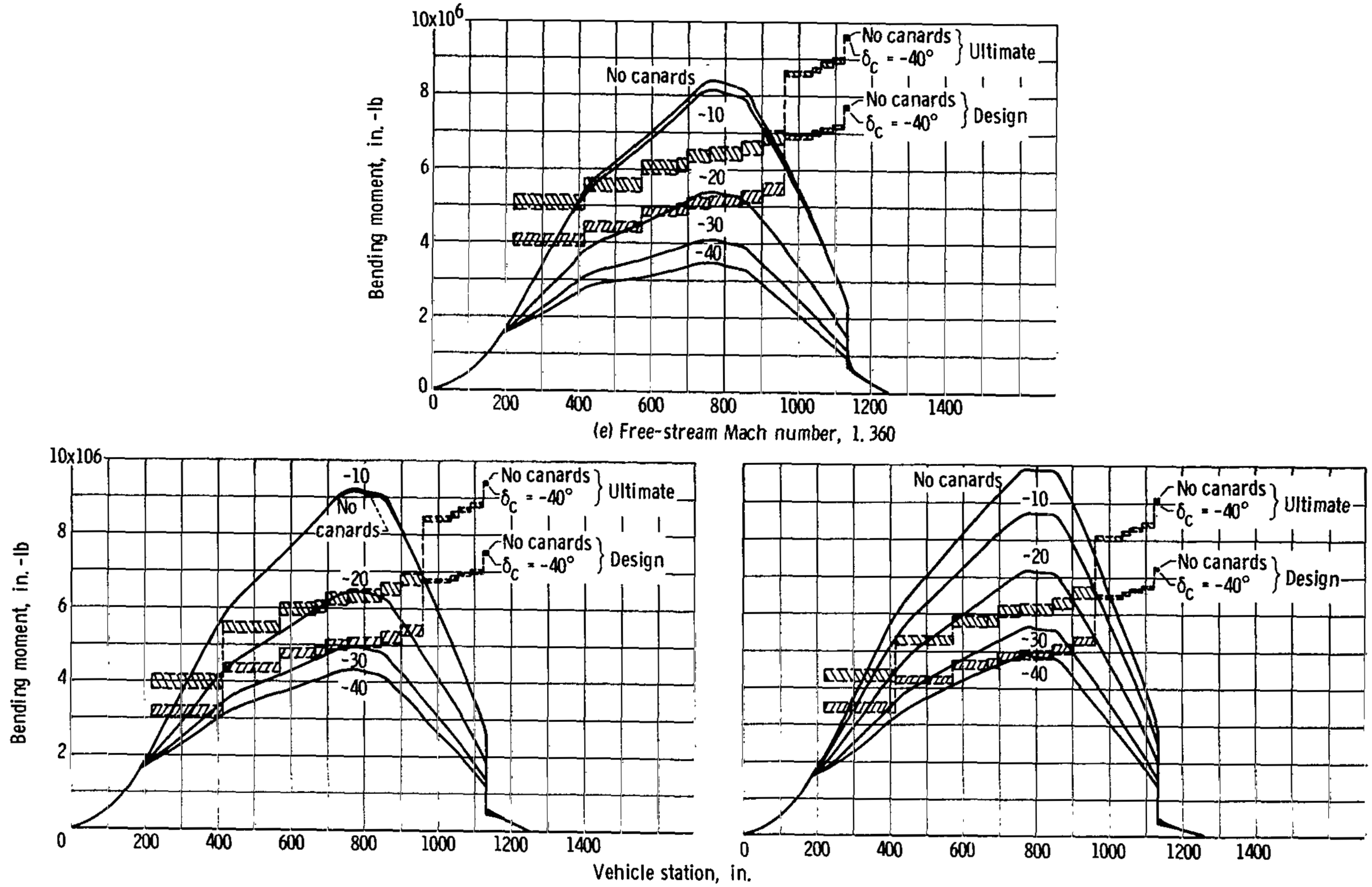
Figure 7. - Effect of canards on vehicle bending moments at 4° angle-of-attack.




(c) Free-stream Mach number, 1.000.

(d) Free-stream Mach number, 1.200.

Figure 8. - Effect of canards on vehicle bending moment at 7° angle of attack.




(e) Free-stream Mach number, 1.360

(f) Free-stream Mach number, 1.560.

(g) Free-stream Mach number, 1.960.

Figure 8. - Concluded.

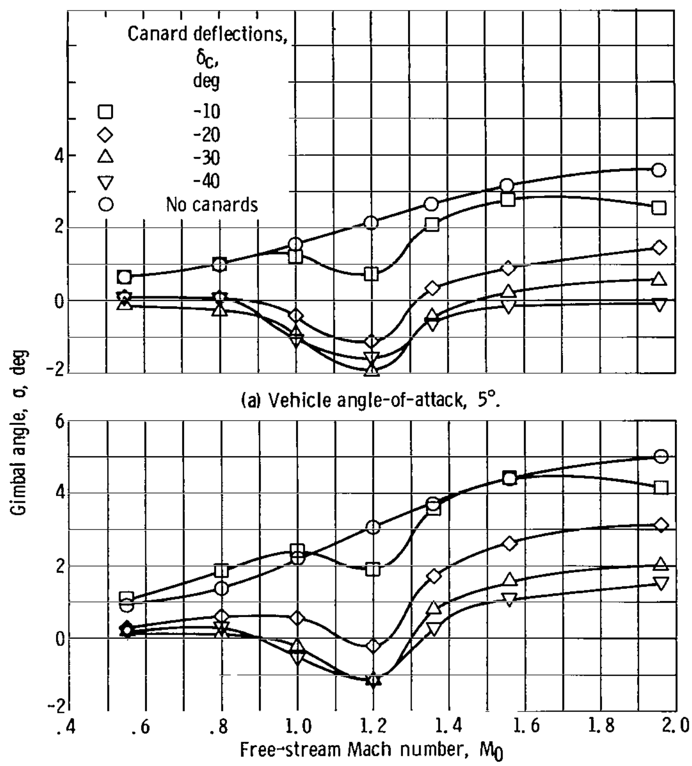



Figure 9. - Effect of canards on engine gimbaling requirement to trim the vehicle.

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